European Commission

JRC VALIDATED METHODS, REFERENCE METHODS AND MEASUREMENTS REPORT

Validation and benchmarking of broadband- and spectral-radiometers

Summary of the 2016 activities of external comparison for performance quality-control

Galleano, R, Zaaiman, W

2016

Joint Research Centre

EUR 28270 EN

This publication is a Validated Methods, Reference Methods and Measurements report by the Joint Research Centre (JRC), the European Commission's science and knowledge service. It aims to provide evidence-based scientific support to the European policymaking process. The scientific output expressed does not imply a policy position of the European Commission. Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use that might be made of this publication.

Contact information
Name: Roberto Galleano
Address: Via E. Fermi 2749, 21027 Ispra (Va) Italy
Email: Roberto.galleano@ec.europa.eu
Tel.: +390332785417

JRC Science Hub
https://ec.europa.eu/jrc

JRC103769

EUR 28270 EN

PDF	ISBN 978-92-79-64123-7	ISSN 1831-9424	doi:10.2790/579648
Print	ISBN 976-92-79-64124-4	ISSN 1018-5593	doi:10.2790/410724

Luxembourg: Publications Office of the European Union, 2016

How to cite this report: Galleano R., Zaaiman W., *Validation and benchmarking of broadband- and spectral-radiometers*, EUR 28270 EN, doi:10.2790/579648

Contents

Abstract

The JRC works together with policy makers, industry and the research community to monitor the progress of photovoltaic technology and help develop the solutions for the future. This directly supports the European Union's objective of attaining an increasing share of renewable energies in the market (20% in 2020 and at least 27% in 2030).

Its European reference laboratory, ESTI, validates electrical performance and lifetime of PV devices based on emerging technologies. Benchmarking, intercomparisons and proficiency tests have a crucial role to play in maintaining and improving the measurement techniques for solar irradiance and to promote transfer knowledge to the European research community. In 2016 the performance based quality check approach on absolute spectral irradiance and broadband radiometry showed consistency of the ESTI primary reference instruments with other primary instruments from Metrological Institutes like NREL (USA), PTB (DE) and PMOD (CH). It is recommended that the laboratory continues to participate in annual inter-comparisons and proficiency tests.

1 Introduction

To support the European Union's political objective of attaining an increasing share of renewable energy in the market, the JRC's European Solar Test Installation (ESTI) works together with policy makers, industry and the research community to monitor the progress of this technology and help develop the solutions for the future.

The photovoltaic (PV) market is at present defined by the price per watt (that is euros per watt peak of rated power of the PV modules); this determination of power is influenced directly by the solar spectral content. As such it relies on the highest level of precision and guarantee of the power measurement for the PV industry (profit), investors and consumers (guarantees of value for money) and the utilities (sizing and guarantee of supply and interoperability). With the annual world PV production exceeding 55 GW in 2015 and a market value only for the module components reaching over €25bn, the methods and standards for the calibration of the power of photovoltaic systems are vital.

This report considers two critical aspects relating to power calibration and energy yield determination for PV devices. The first concerns measurement of the level of direct normal (beam) solar irradiance using broad-band detectors. The most accurate data i.e. that used for reference purposes and for establishing traceability to SI units, are provided by cavity radiometers and pyrheliometers. Such data are critical to:

- the development and deploying solar energy conversion systems
- improving our understanding of the earth’s energy budget for climate change studies
- science and technology applications involving the solar flux

The second aspect concerns measurement of the spectral content of the incoming sun or artificial light solar irradiance. Today's broad portfolio of available photovoltaic technologies makes this information key to the characterization, calibration, and energy yield estimation.

ESTI has a well-established capability for both types of measurement, based on over 20 years' experience with a set of precision instruments. As part of its role to disseminate and manage knowledge, since 2011 ESTI has coordinated and provided the scientific guidance to a European inter-laboratory group to develop and expand the knowledge base of fundamental solar measurements.

Moreover, periodical intercomparisons are part of performance-based quality-control checks for laboratory working according to ISO-IEC 17025 or 9000 standards and highly recommended by world meteorological organization (WMO).

During the comparison campaigns ESTI, together with other participating institutes, organises a series of seminars and discussions to further disseminate the best practices and knowledge to wider scientific/technical audience. Occasions such as this allow not only harmonisation of measurement and instruments but also provide training and education role for the peer laboratory community which is difficult to achieve in conventional seminars.

In this report Chapter 2 describes the activities in spectroradiometry intercomparison campaigns performed at the end of 2015 at PMOD Davos (as ancillary activity of the Twelfth International Pyrheliometer Comparison, IPCXII) and the preliminary results of the International Spectroradiometer Intercomparison (ISRC 2016), held at the ENEA site at Trisaia, Italy in May 2016. Chapter 3 addresses the measurements performed in September-October 2016 at the US National Pyrheliometer Comparison (NPC2016) whose results were issued at the end of October 2016.

2 Spectroradiometer intercomparison

2.1 Purpose of the work, experimental approach

There is a growing request of harmonization of good measurement practices and knowledge transfer in the field of spectrally resolved solar radiation for solar energy applications (e.g. photovoltaics) to make them comparable and directly traceable to SI units

Nowadays, spectroradiometers with different principles of operation (e.g. single-, double- stage rotating grating monochromator or fixed single grating polychromator with photodiode (PD) array or CCD detectors) are routinely used for solar spectrum measurements. Moreover, there is a growing request for comparable, traceable and low uncertainty solar spectrum measurements for calibration and energy yield estimation in photovoltaics. This intercomparison, whose results are summarized in this work, is a good opportunity to raise the awareness on reliable, traceable and low uncertainty measurement of solar spectrum.

Moreover, for the participating Institutions applying a quality system or having an accreditation according the ISO/IEC17025 standard [1], the comparison is an implementation, together with round robin, of the required periodical checks of a performance based quality control system.

For the 2016 comparison the ESTI laboratory brought together on the site of ENEA Trisaia, Rotondella, (MT), Italy 22 researchers from 15 research institutions and industrial partners representing eight European countries to participate in the comparison of broadband and Spectral radiometers. In order to harmonise European wide determination of solar spectral resource ESTI provides through this comparison the baseline calibration standard traceable to SI units and also to the World Radiometric Reference in Davos, Switzerland. The first spectroradiometers comparison campaign in 2011 involved only three member states and it is now the goal to extend this activity to involve participation from all 28 member states.

Thirteen spectroradiometers systems from seven different manufacturers and covering two different technologies (single-stage rotating-grating and fast fixed grating polychromator with single or CCD array detectors) were set to simultaneously measure global normal incidence (GNI) spectral irradiance from 300 to 1700 nm or 300 to 1100 nm; instruments capable [3] or designed exclusively to measure Direct Normal Incidence (DNI) were tested in this condition in the wavelength range from 300 to 1700 nm. The large variety of manufacturers represents a good cross section of today's most used instruments in the PV community.

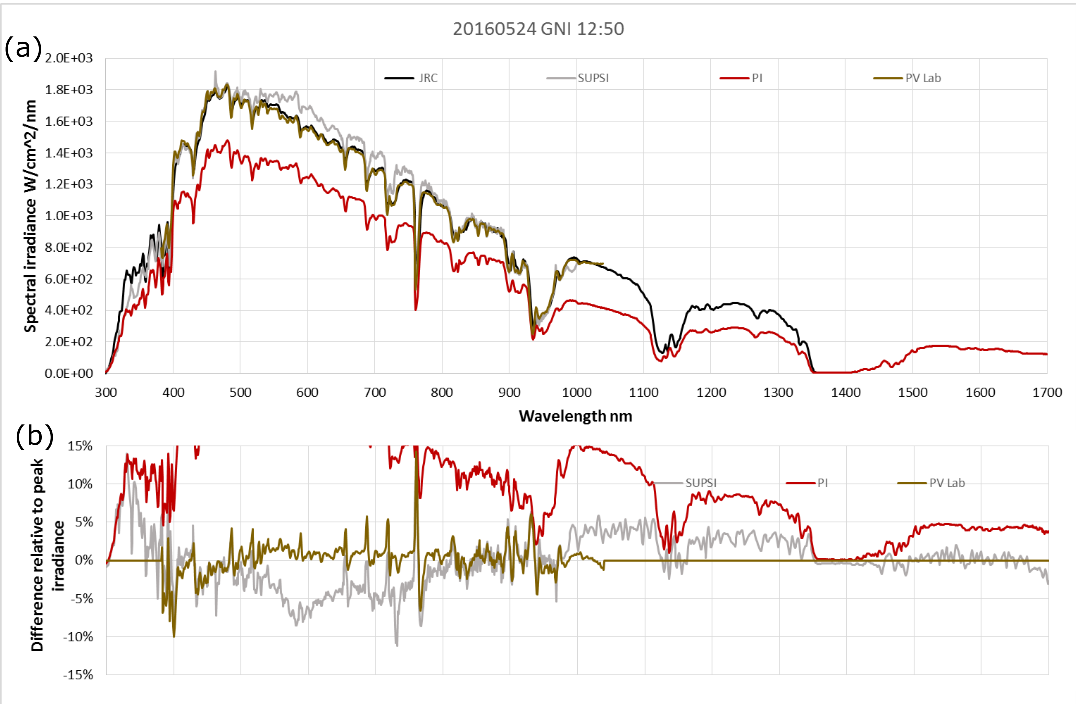
The GNI measurements results from ten laboratories are described in the following. Due to the differences among various instruments in the measurement timing, bandwidth and spectral resolution, specific procedures for data acquisition, synchronization and analysis were developed in order to make the spectroradiometers' output data comparable to each other. Prior to the intercomparison each participating laboratory calibrated their own spectroradiometer(s) following their usual procedures, thus allowing evaluating the instrument performance together with its traceability chain and calibration procedure. Some spectroradiometers were calibrated by an external accredited calibration laboratory while others were calibrated in-house using a calibrated radiometric standard lamp, or at the manufacturer. All participating instruments were mounted on high accuracy solar trackers in order to reduce errors due to instruments pointing. In parallel to the intercomparison a set of cavity radiometers were also in use as reference instruments for total irradiance data. These last assure the direct link to SI units as these cavity radiometers take part to the world radiometric comparison (WRR-IPC) [2], held every 5 year at PMOD-Davos (CH). For clear-sky conditions the corresponding output data obtained from SMARTS model were used for consistency purposes. The dissemination activity performed by JRC in the framework of the intercomparisons is fundamental for maintain a reliable link of the solar spectral measurement performed in the European PV community to the SI quantities and to improve measurements results equivalence among participating institutions.

2.2 Results

In order to compare solar spectra acquired by 'fast' and 'slow' measuring instruments, several sets of average spectra, measured during 7-minute acquisition time series, were analysed. During the time series, the irradiance must remain stable to 1 %, or better, to consider them 'stable' and flagged for analysis. The stability constraint avoids adding errors arising from fast changing weather conditions affecting the output of spectroradiometers in different ways. This constraint limited the useful sky conditions to clear or almost clear. Several analyses were performed on output data both in terms of absolute spectral irradiance and of spectral shape deviation. Diversified data analyses approaches can better separate errors or uncertainty components arising from calibration and systematic effects or from instrument non linearity, internal stray light and drifts as outlined in a previous work [4]. Figure 1 shows typical examples of absolute spectral irradiance deviation analysis performed on a set of simultaneously acquired GNI spectra measured by partners' instruments.

The graph (a) shows the acquired spectra plotted on the same scale one on top of each other, while graph (b) in the same figure shows the wavelength-by-wavelength (Wv-by-Wv) per cent deviation of each spectrum with respect to Lab A spectrum and normalized to its peak irradiance.

Figure 1. (a) GNI solar spectra simultaneously measured by some partners participating to the intercomparison (b) Wavelength-by-wavelength difference with respect to the Lab A spectrum and normalized to its peak irradiance.



By the analysis of these spectra graphs all along the measurement day and during the whole comparison exercise, a first knowledge of the various instruments behaviour may be obtained. However, this intuitive and straight forward approach is able only to highlight macroscopic spectra differences and/or distortion without being able to reveal systematic spectra shifts which may be misinterpreted as is the case for the plot of PI laboratory showing a Wv-by-Wv larger than 15% and a low spectra shape difference as outlined in the following data analysis.

Previous data analysis focusses on the absolute spectral irradiance differences among participating instruments; a different approach can be used to separate systematic effects (e.g. arising from instrument calibration or from instrument time-drift), from non-linearity or distortion. This is important in solar spectrum measurement applied to PV field, where a correct measurement of the shape of incoming solar light is fundamental, whereas the absolute irradiance value is usually measured by other means, often with lower uncertainty (e.g. cavity radiometers, reference solar cells, pyrheliometers, pyranometers etc.). The calibration of a generic PV device at standard test conditions (STC) entails, among others, the correction to the standard spectrum AM1.5 [6]. This correction is performed by applying a mismatch correction factor (MM) accounting only for the relative spectral differences between actual- and standard-spectrum conditions.

An easy comparison of the relative spectral differences among acquired spectra can be done modifying slightly the guidelines described in [5]. The spectral irradiance data from each participating spectroradiometers were integrated into five 100-nm bins from 400 to 900 nm plus one 200-nm bin from 900 to 1100 nm and expressed as ratio to the total irradiance of the same spectrum as integrated in the 400 to 1100 nm band. Afore mentioned standard compares then, the percentage in each bin with the percentage, calculated in the same way, of the AM1.5 standard spectrum to assess the spectrum quality class of a generic solar simulator. In this exercise we substitute the AM1.5 spectrum with the Lab A spectrum as reference. Table 1 reports the percentage differences of the integrated irradiances values in the aforementioned wavelength bands for three participating laboratories relative to a single simultaneous acquisition.

Table 1. Report the percentage difference of the integrated irradiance with respect to JRC integrated irradiance in the six wavelength bands as described in [5]

	Acquisition on 20160524 at 10:45 Wv range / nm					
Lab	400-500	500-600	600-700	700-800	800-900	900-100
PI	-2.75%	-1.62%	-0.40%	1.52%	0.21%	4.71%
Pvlab	-1.51%	0.85%	0.53%	0.47%	0.31%	-0.47%
SUPSI	1.51%	-1.43%	-3.30%	-3.50%	0.07%	7.02%

It is worth noting that the proposed combined data analysis allowed to highlight that PI Lab data, despite having the worst wavelength-by-wavelength average difference, showed low values for the percentage difference of the integrated irradiance, suggesting a systematic scaling factor due, probably, to calibration.

The integrated irradiance analysis as outlined before is systematically made on all stable acquisitions and can be complemented by applying the *En* performance statistics [7] to each bin results. The performance statistics is defined as:

$$En = \frac{MLab_i - Mref}{\sqrt{(ULab_i * MLab_i)^2 + (Uref * Mref)^2}} \quad (1)$$

Where En is the normalized error for the M_{th} bin (unitless), $ULab_i$ and $Uref$ are the reported calibration expanded calibration uncertainty, in percent, for the i_{th} laboratory and the reference, respectively. $MLab_i$ and $Mref$ represent the ratio to the total irradiance for the i_{th} laboratory and the reference, respectively. The calculated deviation of En in eq. 1 involves the establishment of acceptance limits of ± 1; En values within acceptance limit are considered satisfactory and consistent with declared/assigned uncertainty. En values outside acceptance limits highlight inconsistency with estimated uncertainty and/or severe instrument drift from expected performance.

A positive side effect, not always evident, of intercomparisons is the dissemination activity of common, robust and ISO standard referred data analysis approaches.

2.3 IPCXII: Performance of spectroradiometers (from 26/9 to 16/10 2015)

During the IPCXII (from 26/9 to 16/10 2015) three spectroradiometer systems from PMOD Davos, CH, ESTI and PTB Braunschweig, D, were set to measure direct normal incidence (DNI) solar spectral irradiance. Below, comparison preliminary results are reported as received from the project leader laboratory (PMOD). The three spectroradiometric systems involved were in-house developed (PMOD) or commercial one (ESTI and PTB) and previously calibrated by the owning institutions according to their usual calibration chains and procedures. Data analysis was limited to the wavelength range from 300 to 1000 nm due to the limited range of the PMOD systems.

Available spectroradiometers measurements from:

PMOD Davos PSR4: 28 September – 1 October, 12 October, PSR6 : 28 September – 1 October, PSR7 : 28 September – 1 October, 12 October

ESTI-JRC: 30 September, 1 October

Figures 2 and 3 report some examples of acquired spectra during the intercomparison where the acquired spectra are superimposed one on top of each other for a quick and preliminary spectra quality evaluation.

For this exercise, analyses of the ratio of the acquired spectra and of the integrated irradiance in a ± 2.5 nm band at selected wavelengths were performed. Figures 4 and 5 graphically report analysis results [15].

Figure 2. Some examples of simultaneously acquired spectra in the wavelength range 300 to 1000 nm for the three PMOD spectroradiometers plus the JRC-ESTI spectroradiometer system.

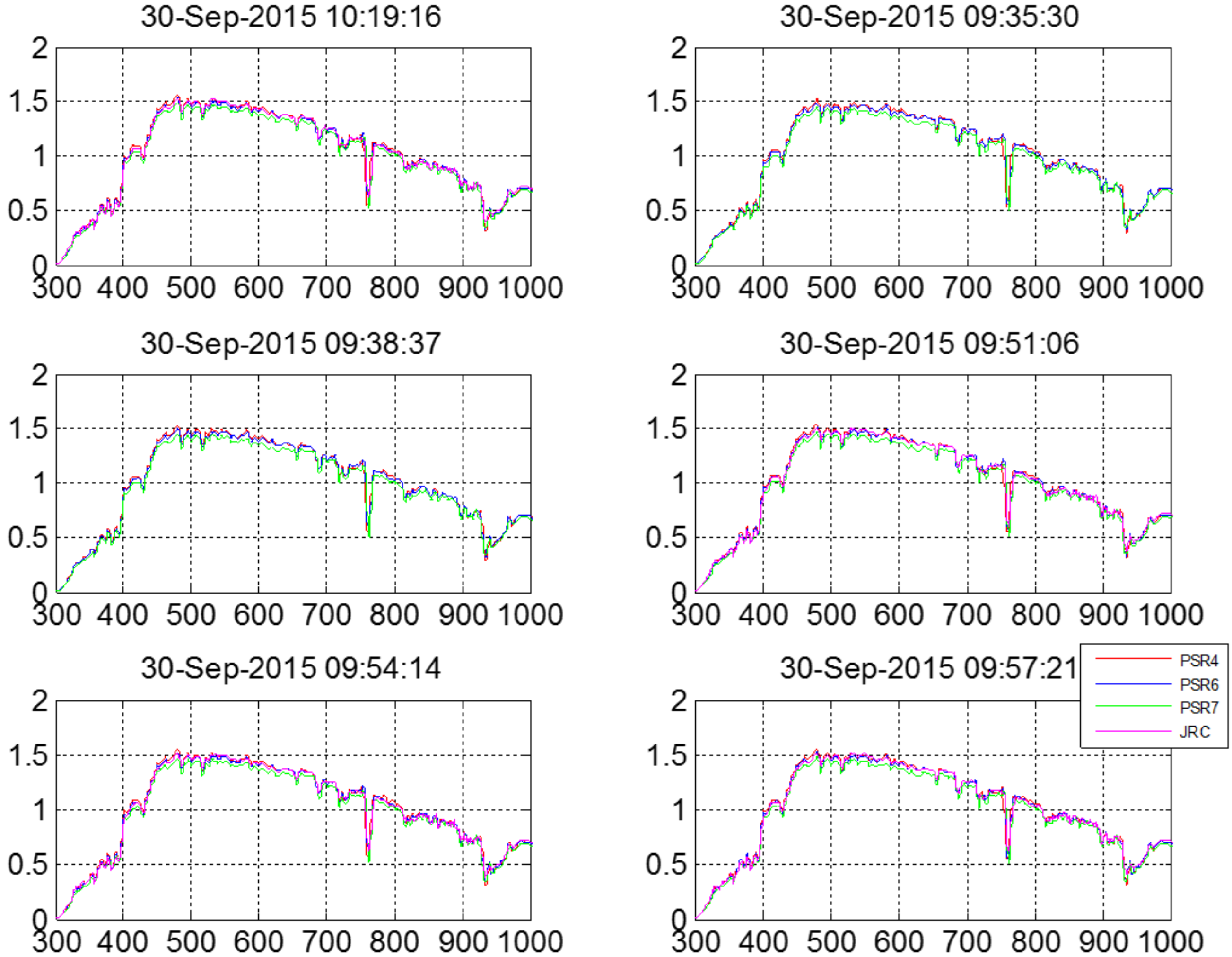


Figure 3. Some examples of simultaneously acquired spectra in the wavelength range 300 to 1000 nm for the three PMOD spectroradiometers plus the JRC-ESTI spectroradiometer system.

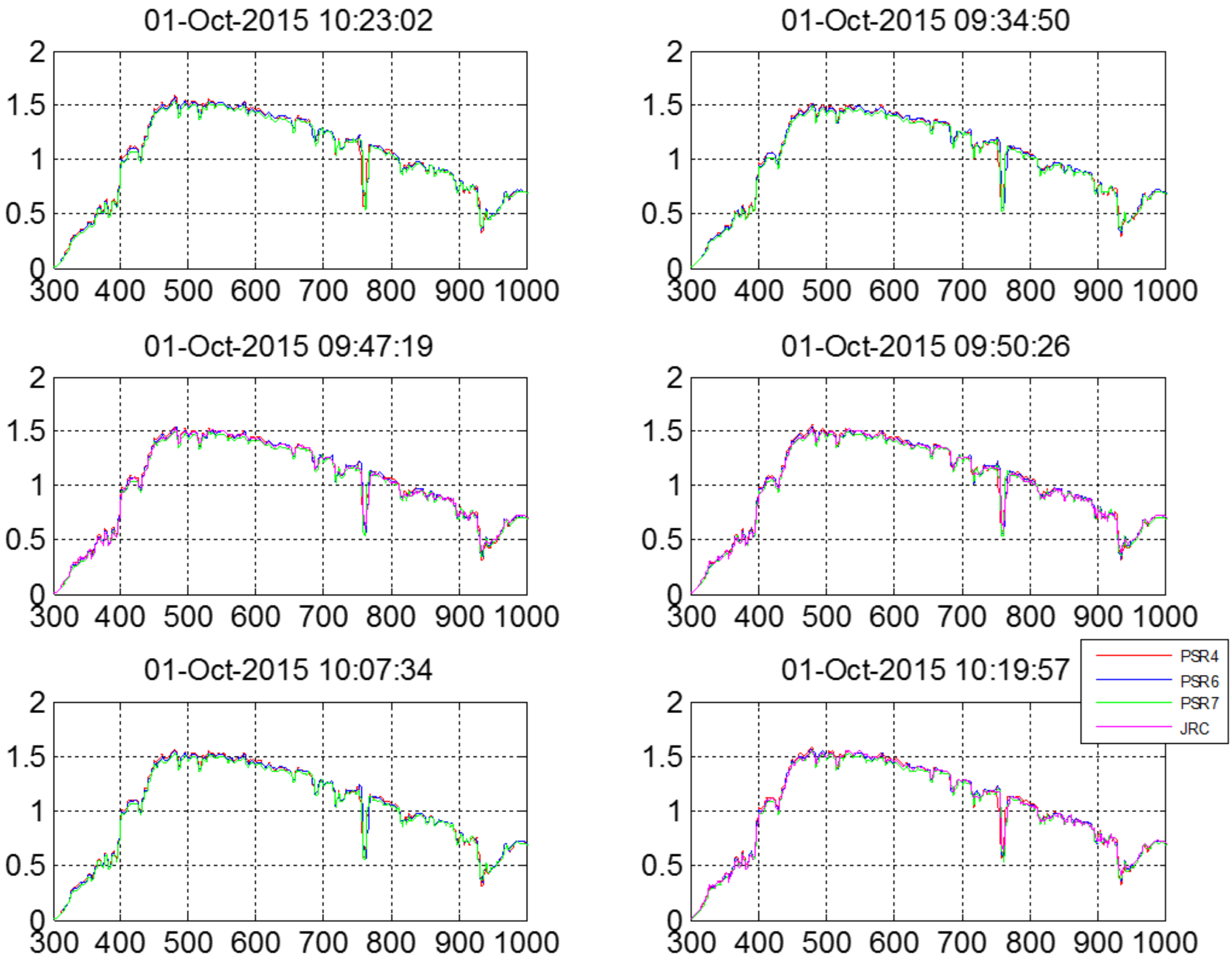


Figure 4. Results of the ratio comparison of the simultaneously acquired spectra by all spectradiometers relative to the average of all PMOD spectroradiometers participating to the intercomparison.

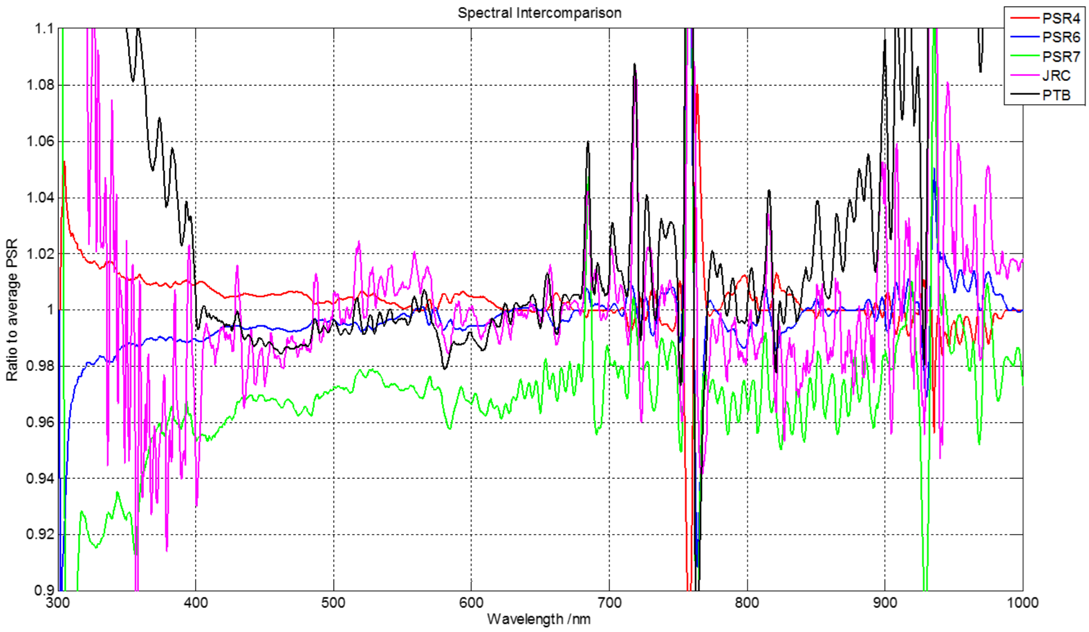
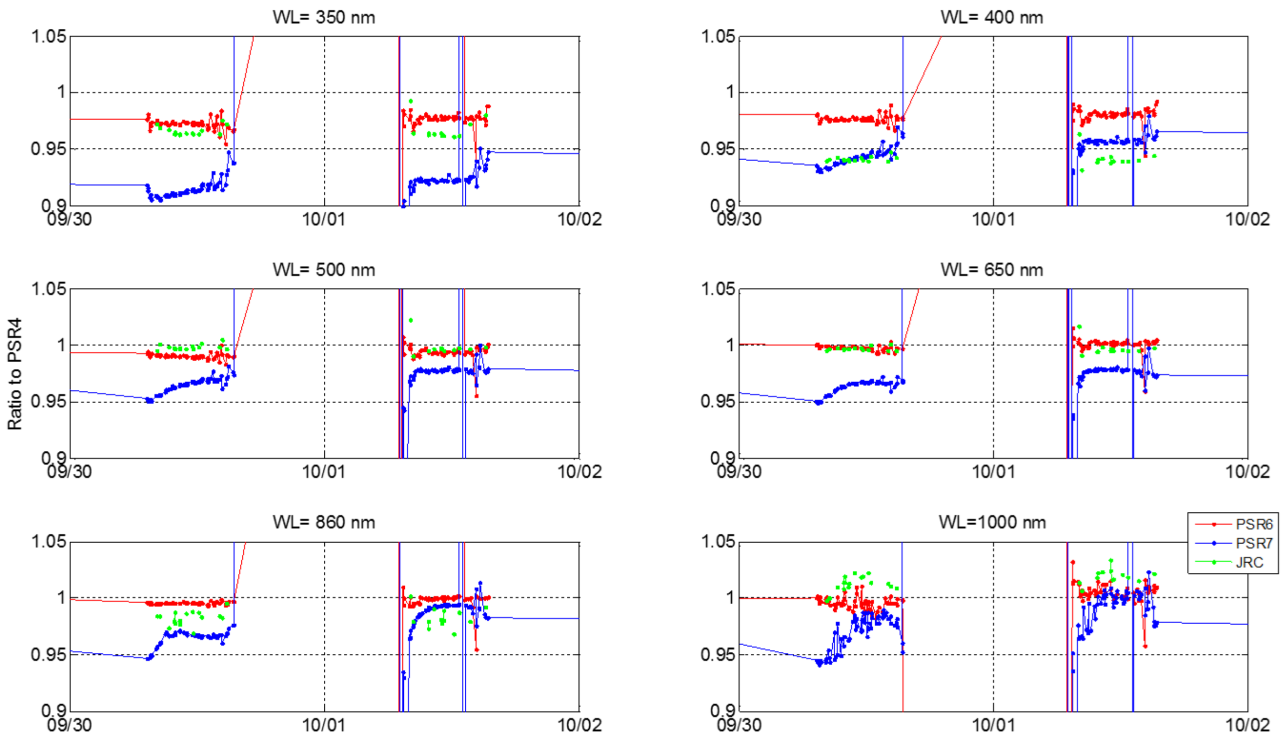


Figure 5. Results of the ratio comparison of the simultaneously spectra acquired by PMOD PSR6 and PSR7, and JRC-ESTI spectradiometers relative to the average of the PMOD PSR4 spectroradiometer. Spectral ratios are averaged over ±2.5 nm



3 Primary and secondary broadband intercomparison

3.1 Purpose of the work, experimental approach

In the late 1970's, the World Meteorological Organisation (WMO) established the Word Radiometric Reference (WRR) as an international standard for direct normal (beam) solar irradiance [12]. The WRR is an internationally recognised, detector-based measurement standard determined by the collective performance of electrically self-calibrated absolute cavity radiometers comprising the World Standard Group (WSG). The WSG is maintained at the PMOD/WRC at Davos, Switzerland. PMOD/WRC Davos has a mandate from the WMO, to transfer the WRR to participating radiometers.

To produce research-quality solar irradiance measurements, accurate radiometer calibrations traceable to an international standard are necessary. Maintaining the high precision of these calibrations / verifications are assured by comparisons at fixed time intervals. Every five years, the PMOD/WRC in Davos, Switzerland hosts an International Pyrheliometer Comparison (IPC) for transferring the WRR to participating radiometers. ESTI has represented the European Commission in each IPC since 2000.

Annually (except for IPC years) ESTI participates in the National Pyrheliometer Comparison (NPC), held at the National Renewable Energy Laboratory (NREL), Golden (CO), USA.

Since 1996, ESTI has developed internal procedures to operate a select group absolute cavity radiometers with direct traceability to the WRR (at Davos), and due to the fact that ESTI primary references directly traceable to this WRR, these references are part of the control radiometers during the NPC's at NREL.

ESTI participation to the above mentioned comparisons, fulfils to the ISO 17025 laboratory accreditation standard, which imposes participation to those comparisons

3.2 NPC2016 Results

ESTI participated to the US NPC 2016 with three primary instruments: cavity radiometers PMO-6 81109, PM-6 911204 and TMI 68835. Data was collected during the reference period (3 days) and submitted to the NREL coordinators. The calibration factors (CF) used were as follows:

PMO 6 81109: 600.0350

PMO6 911204: 601.7356

TMI68835: 1.00383

The evaluation of the data is made with reference to the control radiometers comprising the Primary Reference Standard (PRS) [8, 9 and 10]. A correction value is issued (here called the WRR factor), representing the average relative deviation from the PRS for each of readings (total N). Table 2 compares the 2016 result with the historical irradiance correction values for the three ESTI instruments.

The differences between IPC-XII (2015) and NPC2016 are as follows:

PMO6 81109 : -467 ppm

PMO6 911204 : -136 ppm

TMI 68835 : -164 ppm

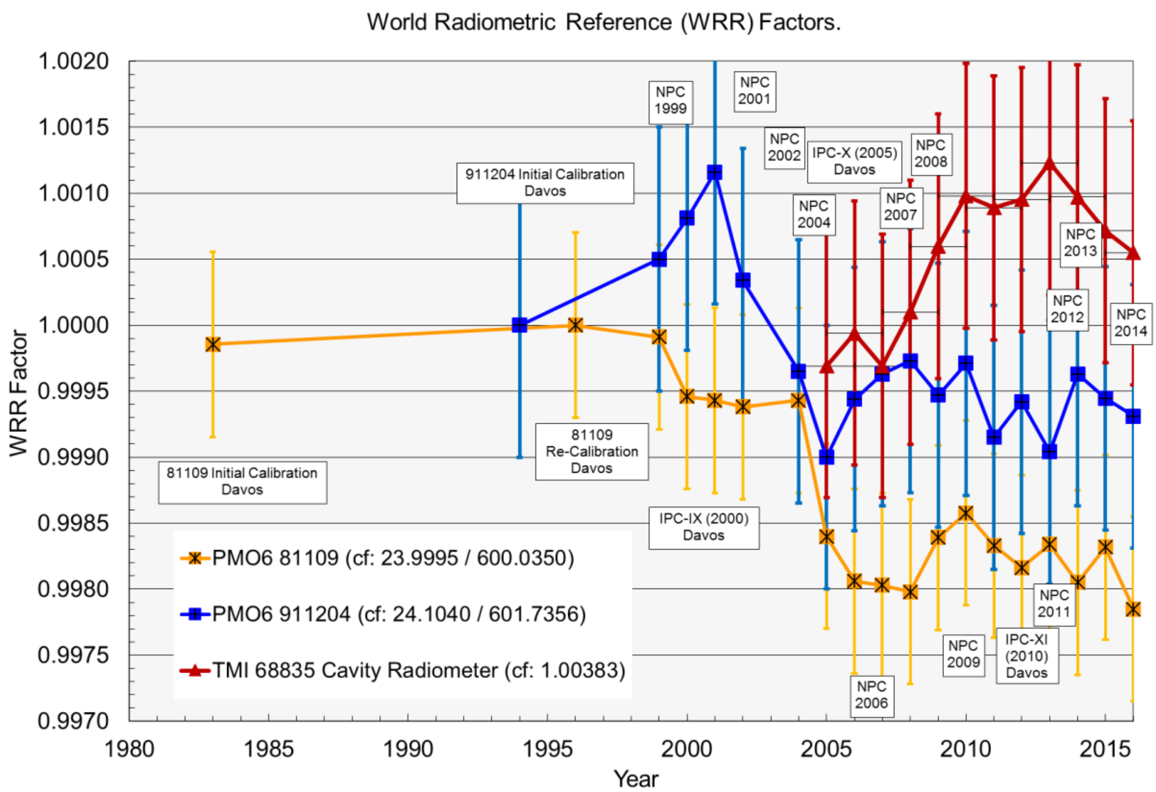
Figure 6 shows the long term behaviour during international inter-comparisons. Note that the correction factors determined during the NPC are not used for calibration work.

As these characterisations are against other cavities (of NREL, Golden (CO), USA) and not against the WSG, these results are used for the verification of the instruments as well as consistency check of the references.

Table 2. Values of irradiance correction factors of the primary instruments from 2010 to 2016 (including NPC 2016).

Year	PMO6-81109			PMO6-911204			TMI68835		
	WRR factor	Sigma [%]	N	WRR factor	Sigma [%]	N	WRR Factor	Sigma [%]	N
2010 IPC	0.998577	0.07	426	0.999711	0.13	436	1.000980	0.10	436
2011 NPC	0.99833	0.06	749	0.99915	0.07	762	1.00089	0.08	2909
2012 NPC	0.99816	0.06	761	0.99942	0.08	767	1.00095	0.08	2890
2013 NPC	0.99834	0.07	498	0.99904	0.07	500	1.00123	0.07	1697
2014 NPC	0.99805	0.06	819	0.99963	0.08	814	1.00097	0.08	3117
2015 IPC	0.998317	0.0623	540	0.999446	0.0942	539	1.000714	0.0764	523
2016 NPC	0.99785	0.06	699	0.99931	0.07	706	1.00055	0.08	2527

Figure 6. The irradiance correction factor for primary reference detectors determined during international inter comparisons. Note that the **y-aix is the relative deviation to the WRR reference, running from -0.3% to +0.2%.**



During the NPC2016 also ESTI's secondary pyrheliometers were compared to the NREL reference standards. The CF [μV/W/m²] used to submit the irradiance data to NREL are:
CH1 930018 : 10.85

CH1 040370 : 10.48

CH1 060460 : 10.07

CHP1 110533 : 7.80

Table 3 compares the historical values of the WRR correction factors at the US NPC intercomparison, while Table 4 shows the values obtained at the last two IPC events at WMOD, Davos (2010 and 2015). Figure 7 shows the historical trend in the WRR correction factors (for CH1 930018 this goes back 22 years).

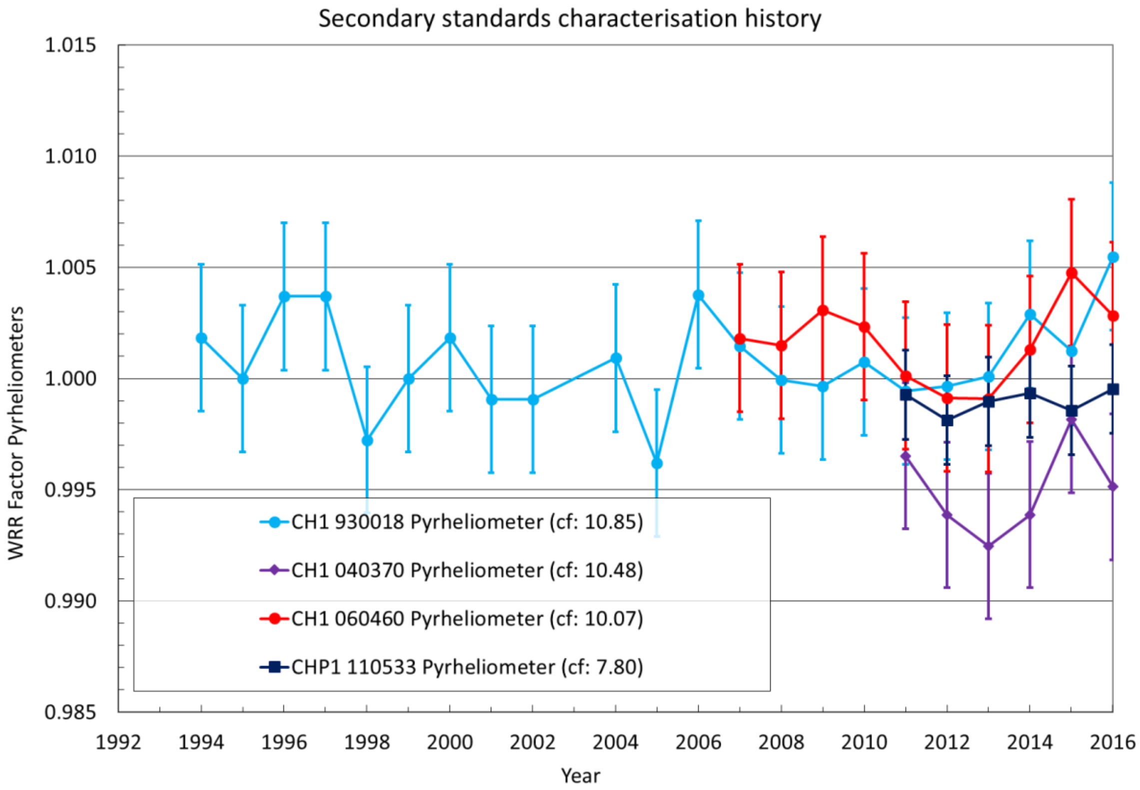
Table 3. Historical WRR correction factors for the ESTI pyrheliometers participating at the US NPC's. Note: The "± value" is the one standard deviation of the correction factor values during the measurement period.

Device (CF)	**Pre 2010**	**2011 (NPC)**	**2012 (NPC/ISRC)**	**2013 (NPC/ISRC)**	**2014 (NPC)**	**2016 (NPC)**
CH1 930018 (10.85)	1.00184 (Y 1994)	0.99943 ± 0.28 %	0.99965 ± 0.28 %	1.00008 ± 0.28 %	1.00288 ± 0.28 %	1.00549 ± 0.28 %
CH1 040370 (10.48)	-	0.99652 ± 0.21 %	0.99387 ± 0.16 %	0.99247 ± 0.16 %	0.99388 ± 0.15 %	0.99514 ± 0.15 %
CH1 060460 (10.07)	1.00182 (Y 2007)	1.00013 ± 0.22 %	0.99914 ± 0.13 %	0.99910 ± 0.12 %	1.00130 ± 0.14 %	1.00282 ± 0.14 %
CHP1 110533 (7.80)	-	0.99927 ± 0.17 %	0.99814 ± 0.18 %	0.99897 ± 0.29 %	0.99936 ± 0.14 %	0.99953 ± 0.14 %

Table 4. Historical WRR correction factors for the ESTI pyrheliometers participating in IPC's at PMOD, Davos (CH). Note: The "± Value" is the one standard deviation of the correction factor during the measurement period.

Device (CF)	**2010 (IPC-XI)**	**2015 (IPC-XII)**
CH1 930018 (10.85)	1.000748 ± 0.33 %	1.00219 ± 0.20%
CH1 040370 (10.48)	-	0.99905 ± 0.21%
CH1 060460 (10.07)	1.002334 ± 0.20 %	1.00539 ± 0.15%
CHP1 110533 (7.80)	-	0.99961 ± 0.22%

Figure 7. The irradiance correction factor determined during international inter-comparisons.



3.3 Proficiency test as validation parameter for instruments participating to inter-comparisons

Proficiency testing determines the performance of an individual laboratory for specific tests or measurements and is used to monitor a laboratory's performance. Interlaboratory comparisons are a form proficiency testing.

There are different ways to evaluate the results of a proficiency test, as mentioned in ISO 13528 [11]. For the type of proficiency tests considered here, an En-value can be calculated for the result reported by NREL for a the primary reference standards compared to reference values determined during the IPC-XII at PMOD, Davos, (CH). This is defined as follows:

$$En = \frac{WRR_{Lab} - WRR_{ref}}{\sqrt{(U_{95}Lab)^2 + (U_{95}ref)^2}}$$

Where in this case:

WRR_{Lab} is the value reported by NREL

WRR_{Ref} is the reference value (reported by PMOD, Davos (CH))

$U_{95}Lab$ is the uncertainty reported by NREL, and

$U_{95}ref$ is the uncertainty of the reference value (reported by PMOD Davos (CH)

The uncertainties are expressed using k=1.96, which corresponds to a 95 % coverage.

The result is considered successful, if the result of the proficiency test is $-1 \leq E_n \leq 1$. In this case the laboratory (NREL) agrees with the reference value within the stated uncertainty of the two. Based on a number of assumptions, this is expected to be the case at least 95 % of the time.

For the ESTI cavities, the E_n numbers calculated with reference to the results of IPC-XII [8] and NPC2016 (as reported into the NREL report [9]) are:

PMO6 81109 : 0.090

PMO6 911204 : 0.026

TMI 68835 : 0.030

Using the same algorithm for the secondary pyrheliometers the results are:

CH1 930018 : - 0.512

CH1 040370 : + 0.408

CH1 060460 : + 0.306

CHP1 110533 : - 0.126

All of the above mentioned values are well within the band of $-1 \leq E_n \leq 1$ and therefore the outcome of the inter-comparison is considered valid and confirms the stability of the instruments.

A further issue concerns the assessment of historical trends in the WRR correction factor for each instrument, even if considered stable according to the above proficiency test result. In this context it needs to be recognised that in principle the variations in the WRR correction factor can be influenced by variations in the performance of the reference group as well by that of the instrument itself.

One approach to further investigate this aspect is to calculate the En value for successive estimates of the WRR correction factor, using the following formula

$$En = \frac{WRR_{year} - WRR_{(previous\ year)}}{\sqrt{(U_{95}year)^2 + (U_{95}previous\ year)^2}}$$

with

WRR_{year} : the WRR value assigned of the current year

$WRR_{previous\ year}$: the WRR value assigned of the previous year

$U_{95}year$: the U_{95} uncertainty calculated using data of current year, and

$U_{95}previous\ year$: the U_{95} uncertainty calculated using data of current year

The U_{95} of the year is calculated as:

$$U_{95}year = \pm 1.96 * \sqrt{u_A{}^2 + u_B{}^2}$$

where:

u_A = standard deviation of the WRR value of the instrument during that year

u_B = pooled standard deviation of the reference for that year without the uncertainty component of the WRR to SI - units.

The pooled standard deviation of the reference is 0.06% for 2015 and 2016. For 2012 – 2014 the pooled standard deviation is 0.07%, as reported in [8], [9] and [10]. No pooled standard deviation is available for 2011.

Table 5 shows the resulting E_n values for all instruments (primary and secondary) over the years 2012 to 2016, as well as the standard deviation. For instance, a clear qualitative link with stability is apparent for CHP1 110533, comparing the low value of the standard deviation in the E_n number with the minimal historic variation in the WRR correction factor for 2011 to 2016, as clearly seen in Figure 7.

Table 5. En value between the WRR correction factors for successive years for the ESTI cavities and pyrheliometers.

Device (CF)	**2012 - 2013 (NPC)**	**2013 - 2014 (NPC)**	**2014 - 2015 (IPC)**	**2015 - 2016 (NPC)**	**E_n Average**	**E_n St. Dev**
PMO6 81109	-0.066	+0.109	-0.108	+0.197	+0.03	0.14
PMO6 911204	0.133	-0.207	+0.061	+0.048	+0.01	0.15
TMI68835	-0.097	+0.098	+0.098	+0.060	+0.04	0.09
CH1 930018	-0.054	-0.350	+0.223	-0.627	-0.20	0.37
CH1 040370	+0.289	-0.299	-0.802	+0.536	-0.07	0.60
CH1 060460	+0.010	-0.536	-0.810	+0.473	-0.22	0.57
CHP1 110533	-0.119	-0.059	+0.142	-0.162	-0.05	0.13

4 Conclusions and Recommendations

Benchmarking, intercomparisons and proficiency tests have a crucial role to play in maintaining and improving the measurement techniques for solar irradiance and to promote transfer knowledge to the European research community. Moreover, periodical intercomparisons are part of performance-based quality-control checks for laboratory working according to ISO-IEC 17025 or 9000 standards and highly recommended by the World Meteorological Organization.

In 2016 ESTI played a leading role in both spectroradiometer and pyrheliometer intercomparisons with international and European organisations from scientific and industrial sectors. In particular ESTI's participation in the International Spectroradiometer Intercomparison provides the opportunity to transfer the WRR traceability of the World Standard Group of broadband radiometers to the European participating organisations.

Analysis of the results for spectroradiometers at the 2016 International Spectroradiometers Intercomparison are on-going and shows promising results confirming that absolute and relative spectral irradiance comparison proves to be a good approach to separate instrument non linearity and distortion effects from calibration systematic effects. The harmonization efforts deployed since the first intercomparison obtained a reduction of data dispersion in the calculation of the spectral mismatch factor from 3 % to below 1 % for the best-in-class participating laboratories.

The results of the 2016 US National Pyrheliometer Intercomparison (NPC) showed that all the ESTI broadband reference instruments (cavity radiometers and pyrheliometers) have maintained fully acceptable values of the correction factors to WRR reference, with En values well within the limits of ± 1.0. These results confirm the validity of ESTI's traceable chain for solar irradiance measurement, which underpins the laboratory's capability to provide best-in-class power calibration uncertainty for PV modules.

Overall, this performance based quality check approach on absolute spectral irradiance and broadband radiometry showed consistency of the ESTI primary reference instruments with other primary instruments from Metrological Institutes like NREL (USA), PTB (DE) and PMOD (CH).

It is recommended that

a) The laboratory continues to participate in annual inter-comparisons and proficiency tests.

b) The procedure described here for the determination of a “stable” irradiance instrument should be introduced into the ESTI quality system, thus avoiding subjective interpretation.

References

[1] ISO/IEC 17025:2005, General requirements for the competence of testing and calibration laboratories, International Organization for Standardization, ISO Central Secretariat, Chemin de Blandonnet 8, CP 401 1214 Vernier, Geneva, Switzerland

[2] Finsterle, W., (2011), WMO International Pyrheliometer Comparison IPC-XI Final Report,WMO IOM Report No., 108

[3] Guide to meteorological instruments and observations, WMO-No-8 Secretariat of the Wolrd Meteorological Organisation, 2006, Geneva, Switzerland

[4] R. Galleano et aliis: 'Results of the fifth international spectroradiometers comparison for improved solar spectral irradiance measurements and related impact on reference cell calibration.' IEEE Journal of Photovoltaics (Volume: 6, Issue: 6, Nov. 2016) Page(s): 1587 – 1597, DOI: 10.1109/JPHOTOV.2016.2606698

[5] ISO/IEC 60904-9:2007 Photovoltaic devices - Part 9: Solar simulator performance requirements, International Organization for Standardization, ISO Central Secretariat, Chemin de Blandonnet 8, CP 401 1214 Vernier, Geneva, Switzerland

[6] ISO/IEC 60904-7 Photovoltaic devices - Part 7: Computation of spectral mismatch error introduced in the testing of a photovoltaic device, International Organization for Standardization, ISO Central Secretariat, Chemin de Blandonnet 8, CP 401 1214 Vernier, Geneva, Switzerland

[7] ISO/IEC 17043:2010 Conformity assessment—General requirements for proficiency testing, ISO Central Secretariat, Chemin de Blandonnet 8, CP 401 1214 Vernier, Geneva, Switzerland

[8] IPC-XII report. WMO report 124 - 2016

[9] NPC reports of 2012 to 2014 (NREL/TP-3B10-63050) and 2016 (NREL/TP-3B10-67311)

[10] Calibration certificates from NPC 2011

[11] ISO 13528:2005: Statistical methods for use in proficiency testing by interlaboratory comparisons, ISO Central Secretariat, Chemin de Blandonnet 8, CP 401 1214 Vernier, Geneva, Switzerland.

[12] Fröhlich, C.,"History of solar radiometry and the World Radiation Reference", Metrologia 28, 1991, pages 111-115.

[15] Groebner, J, PMOD/WRC, Dorfstrasse 33, Davos Dorf (CH), Private communication.

List of figures

List of tables

LD-NA-28270-EN-N

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

Joint Research Centre

EU Science Hub

Publications Office

doi:10.2790/579648

ISBN 978-92-79-64123-7